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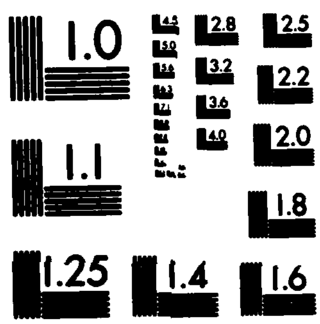

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ANGULAR DEVIATION AND ITS EFFECT ON HUD-EQUIPPED AIRCRAFT WEAPONS DELIVERY ACCURACY

LOUIS V. GENCO, Lt Col, USAF
AIR FORCE AEROSPACE MEDICAL RESEARCH LABORATORY

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At present, all forward windscreens (or canopies) installed on Hud-equipped aircraft are measured to determine their angular deviation, or induced aiming error. Standards have been set to accept only those transparencies which cause little aiming error, and at least one aircraft HUD fire control computer is provided with a means to compensate for the remaining error. This report is a summary of several of the multitudinous methods used to measure angular deviation for most HUD-equipped aircraft, with an explanation of the comparative accuracy of each method when applied to weapons aiming at

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operational sighting ranges. The advantages and disadvantages of each quality control system are discussed, and an attempt is made to reconcile the values of each system for sighting accuracy comparisons. A recommendation is made for a standardized method of measurement which is relatively error free, and best relates to operational use of the aircraft.

PREFACE

The research described in this document was performed at the Air Force Aerospace Medical Research Laboratory, Human Engineering Division, Crew System Effectiveness Branch in the Windscreen Evaluation Facility, Wright-Patterson AFB, Ohio, under Work Unit 7184-18-02. Funding for this effort was provided by the Air Force Wright Aeronautical Laboratories, Flight Dynamics Laboratory, Vehicle Equipment ADP Branch.

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TABLE OF CONTENTS

	Page
INTRODUCTION	3
HOW A HUD PROJECTS A DISPLAY	4
DEFINITIONS	5
CLASSIFICATION OF MEASUREMENT TECHNIQUES	7
INSTALLED ANGLE MEASUREMENTS	7
MEASUREMENTS ALONG THE NORMAL	8
SUMMARY OF TECHNIQUES	9
CONCLUSION AND RECOMMENDATIONS	15
APPENDICES	15
A. Tables of Lateral Displacement for Various Thicknesses of Material Similar to those used in Aircraft Transparencies	15
B. Summary of Methods used to measure Angular Deviation in HUD-equipped Aircraft	17
C. Computation of Actual Angular Deviation experienced as a result of Tilting a Transparency	18
REFERENCES	19

LIST OF ILLUSTRATIONS

Figure		Page
1	HUD Data Projection with Combining Glass	4
2	Effect of Interposing Transparency on Projection	5
3	Normals for Curved and Flat Surfaces	5
4	Angular Deviation in a Transparency	6
5	Lateral Displacement in a Transparency	7
6	Effect of Rotation of the Transparency on Angular Deviation as Measured Along a Normal	8
7	Method of Measuring the A-10 Windshield	9
8A	Method of Measuring the F-5 Canopy	10
8B	Method of Measuring the F-5 Windshield	10
9A	Method of Measuring the F-15 and F-18 Windshield (Azimuth)	12
9B	Method of Measuring the F-15 and F-18 Windshield (Elevation)	12
10A	Double Vision Method for F-111 Windscreens	14
10B	Laser Method for F-111 Windscreens	14

LIST OF TABLES

Table		
1	Sighting Errors Due to Laterial Displacement Contamination of Angular Deviation Measurements made at Installed Angle	7
2	Sighting Errors Due to Rotation of the Transparency from Measurements Along the Normal	8

INTRODUCTION

Today's fighter and fighter-bomber aircraft are weapon platforms capable of performing awesome feats when properly maintained and flown. Each manufacturer takes pride in providing his product with distinct advantages in survivability, maneuverability, flexibility and a host of other attributes. It is the differences in these attributes that contribute to the success or failure of the airframe as a successful weapon system.

One of the differences among aircraft lies in the method of aiming the onboard weapons. Many recent fighters are equipped with a Head-Up Display (HUD) which allows the pilot to maintain visibility of the external world while monitoring critical instrument readings. The HUD also can project a sight or pipper so it appears to fall on the target of choice, thus aiding the pilot's ability to deliver his ordinance effectively.

HUD-equipped aircraft sighting accuracy can be significantly affected by the optical quality of the windscreen interposed in the pilot's line of sight. The image of the pipper or other HUD-projected imagery is reflected from the HUD combining glass directly into the pilot's eyes, whereas the image of the target must pass through both the windscreen and the combining glass. The interposition of a thick, curved, slanted or wedgy windscreen moves the image of the target from the actual location of the target itself, while leaving the pipper unaffected. This disparity between pipper and target location can lead to degraded weapons delivery accuracy unless the windscreen or HUD can compensate for the error.

At present, all forward transparencies (windscreens or canopies) installed on HUD-equipped aircraft are measured to determine their angular deviation, or induced aiming error. Standards have been set to accept only those transparencies that cause little aiming error, and one aircraft HUD fire control computer attempts to compensate for the remaining error. No two methods of measurement appear to be similar in either technique or results. Although most of the methods purport to indicate angular deviation, their results will yield conflicting data which are not readily converted from one method to another.

HOW A HUD PROJECTS A DISPLAY

Head-Up Displays provide critical flight information, and a "pipper" which acts as the sighting indicator. Figure 1 diagrams how the HUD provides these data. A Cathode Ray Tube (CRT) in the HUD body projects collimated light upwards to a thick glass beamsplitter or combining glass. A portion of this light reflects from the glass and continues back eventually to enter the pilot's eyes. Since the light is collimated (the light rays are nominally parallel), the pilot sees the projected information as though it were located at optical infinity. The image of the pipper and calligraphics is located in front of the aircraft for the same reason the reflection of your face is "behind" your bathroom mirror. In optical terms, this is a "virtual" image because one can neither touch it nor project it on a screen. In other words, the image is in the observer's eye, not at the point in space where it appears to be.

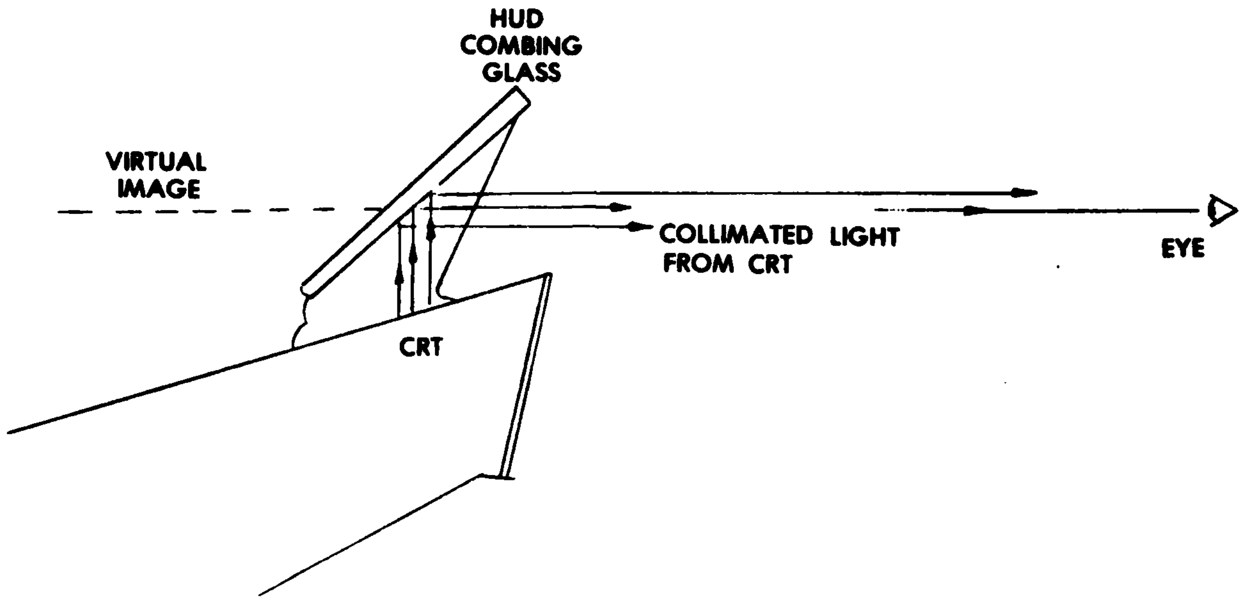

FIGURE 1. HUD DATA PROJECTION WITH COMBINING GLASS

The large exit pupil in the HUD allows the pilot to move his head within certain limits and still see the information projected by the HUD. If he moves his head too far, however, some of the information will be vignetted or prevented from reaching his eyes. Within the envelope of movement permitted by the exit pupil, head motion will not cause parallax or motion of the pipper, graphic or alphanumeric data with respect to the target in the outside world. There is essentially no parallax between distant targets and the pipper in a correctly adjusted HUD because (1) light from the target object is collimated (or very nearly so), as is the light from the pipper; and (2) the light rays from the target are parallel to the rays from the pipper. As long as both of these conditions are met, the pilot sees the HUD pipper superimposed on his target of choice wherever that target appears in the field of view (FOV) of the HUD. If the avionics are properly aligned, and the stores are delivered to the location indicated by the pipper, they will then strike the target with no sighting error.

This ideal situation does not exist in the real world because an additional optical element is placed in the path of light between the target and the pilot's eyes. This element is the aircraft's transparency (windshield or canopy). The transparency changes the apparent position of the target while leaving the pipper unaffected. The light from the pipper does not pass through the canopy, so it is not influenced by canopy optics. Figure 2 shows the transparency in place, intercepting the light from the target. Since the light from the HUD does not pass through the canopy (at least not in the forward area), it cannot be affected by canopy optics. As a result of this, the image of the target as seen by the pilot is neither located at the same position as the actual object, nor is the target located at the point indicated by the pipper (unless the canopy is rotated out of the optical path between target and eye). The stores may be delivered to the area indicated by the pipper, but the pipper indicates a false location of the target.

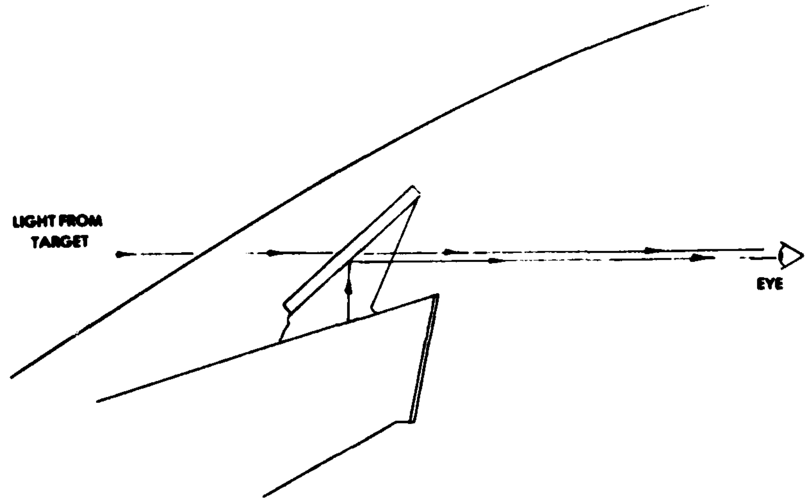

FIGURE 2. EFFECT OF INTERPOSING TRANSPARENCY ON PROJECTION

DEFINITIONS

There are several reasons why this shift in location occurs. One, such as incorrect collimation, are due to HUD optical errors. Others, such as lateral displacement and angular deviation, are due to transparency optical errors. Lateral displacement of light rays occurs whenever light passes through a transparency at an angle other than the normal. A "normal" is defined as an imaginary line perpendicular to the surface of the transparency. For flat surfaces, the normal is at right angles or perpendicular to the surface; for curved surfaces, the normal is a continuation of the radius of curvature. Figure 3 depicts these two definitions.

LATERAL DISPLACEMENT

The term "lateral displacement" describes the linear amount of shift or change in position induced by the passage of light through any thick, tilted transparency. This amount is constant over distance, i.e. it does not increase with increasing range, and is linear rather than angular in nature.

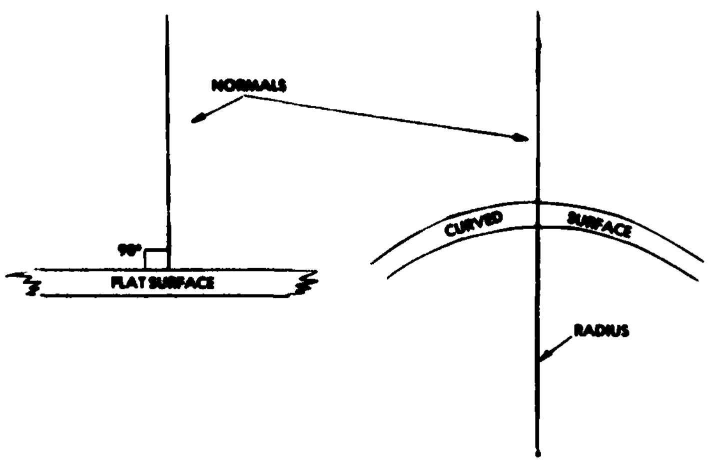

FIGURE 3. NORMALS FOR CURVED AND FLAT SURFACES

The amount of shift may be calculated using the equation:

$$LD = T * \frac{SIN\ a * (\sqrt{n'^2 - n^2 * SIN^2\ a} - n * COS\ a)}{\sqrt{n'^2 - n^2 * SIN^2\ a}}$$

where LD = Lateral Displacement
T = actual thickness of the part,
a = angle between the line of sight and the normal (the angle of incidence),
n' = index of refraction of the material
n = index of refraction of air.

Appendix A contains tables of lateral displacement for various thicknesses of material similar to those used in the aircraft transparencies included in this report. The angles used in the calculation are representative of a wide variety of sighting angles found in many aircraft.

Lateral displacement has little effect on weapon sighting accuracy in the real world because errors of a fraction of an inch are negligible, whether this fraction is at 100 feet or 3000 feet. Unfortunately, lateral displacement affects the accuracy of measurement of angular deviation, which is a critically important parameter of the transparency, because most methods do not distinguish between target shifts caused by lateral displacement and those caused by angular deviation. Since most quality control measurements are performed at relatively short ranges (100 feet or less), the shifts caused by lateral displacement are much larger than those caused by angular deviation; if these shifts are interpreted as being entirely due to angular deviation, erroneous results will ensue.

ANGULAR DEVIATION

The term "angular deviation" describes the angle between light rays from the actual target (object) and the line of sight to the apparent or perceived target (image). Figure 4 shows this relationship. A very small angular deviation can cause the image of the target to shift a considerable amount from its actual position. Since this is an angular error, image shift is related to the distance between target and transparency. If the image of a target at 10 feet were shifted only 1 inch by angular deviation, it would be shifted over 8 feet at 1000 feet or 25 feet at 3000 feet.

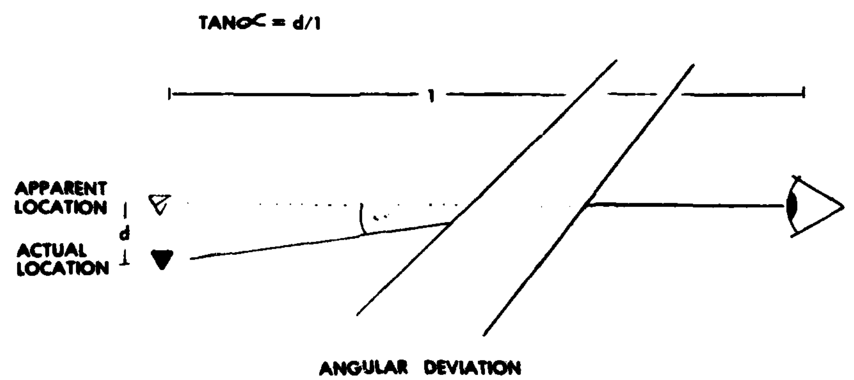

FIGURE 4. ANGULAR DEVIATION IN A TRANSPARENCY

Target image shift may be calculated by using the equation:

$$D = TAN\ a * R$$

where a = the angular deviation,
D = the distance between the apparent and actual positions of the target (image shift)
R = Range to target

CLASSIFICATION OF MEASUREMENT TECHNIQUES

All methods for measuring angular deviation in HUD-equipped aircraft can be grouped into two classifications:

(1) Transparency measured at installed angle (as if it were in place aboard the aircraft).
(2) Transparency measured along a normal (at right angles) to its surface.

Both of these methods have advantages and disadvantages, some of which are explained here.

INSTALLED ANGLE MEASUREMENTS

If a flat transparency (even a perfectly flat optical plate with parallel sides) is tilted so the line of sight no longer coincides with the normal, any object seen through the transparency will have its apparent position shifted in the direction of tilt. The amount of shift is dependent on the thickness of the material, its index of refraction, and the amount of tilt, but NOT on the distance of the object to the transparency or eye. Figure 5 shows how a thick optically flat plate causes this to happen.

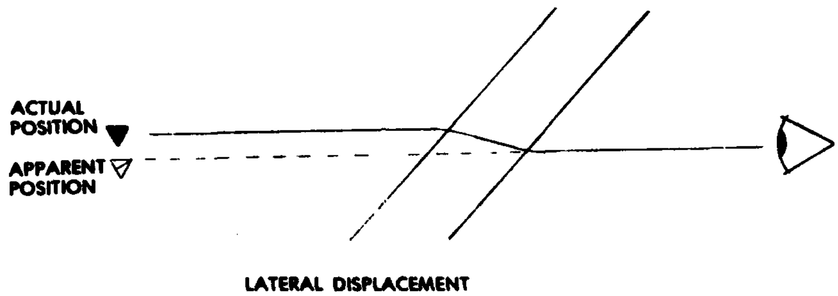

FIGURE 5. LATERAL DISPLACEMENT IN A TRANSPARENCY

Since most current methods of measuring angular deviation do not discriminate between image position shifts caused by angular errors and those caused by linear errors, all image shifts will be interpreted as being due to angular errors. Even small lateral shifts measured at relatively close ranges will be erroneously interpreted as if they were large lateral shifts at more distant sighting ranges. (Recall the example of a 1-inch shift at 10 feet resulting in a 25-foot error at 3000 feet).

Table 1 shows the induced errors caused by lateral displacement being misinterpreted as due to angular deviation for several test methods. The table assumes the transparency to be a "perfect" part with parallel surfaces, measured at the installed angle per specification method. The errors listed are for lines of sight passing near the boresight position only, and only for angles of incidence of between 65 and 85 degrees. These angles of incidence approximate the pilot's line of sight for viewing the "straight ahead" position to a depression angle of about 15 degrees. This error will increase as the line of sight is further depressed or as the curvature of the part causes an increased optical angle of incidence. "Error" is defined as the angular difference between actual target position and that predicted by the existing test method. If the HUD pipper is aligned according to existing angular deviation specifications, stores delivered at any range other than that used while being tested will miss the pipper — indicated delivery point by at least the amount indicated. This table does not show errors in aircraft whose transparencies are measured at a normal to the surface of the window since lateral displacement is not a factor in the latter system of measurement.

TABLE 1

Sighting Errors Due to Lateral Displacement Contamination of Angular Deviation Measurements Made at Installed Angle

Aircraft	(W/S thick)	Test Distance	Error
F-5	0.71 in acrylic	151 in	0.35 - 0.54 MR
F-16	0.63 in poly	100 ft	0.31 - 0.48 MR
	0.75 in composite	100 ft	0.37 - 0.57 MR
	0.63 in poly	infinity	0
	0.75 in composite	infinity	0

MEASUREMENTS ALONG THE NORMAL

Measuring the angular deviation along a normal eliminates lateral displacement as a source of error, but introduces a problem — how does one relate angular deviation measured along a normal to that experienced by the pilot with the transparency in the installed position? Figure 6 shows the changes in angular deviation as the line of sight is rotated away from the normal. This curve represents the error induced by measuring angular deviation along a normal, while using the transparency at its installed angle. The curve is an approximation, and accurate calculations require exact knowledge of not only the angle of tilt of the transparency, but the angle between a normal to its surface and the pilot's line of sight for all possible positions of gaze when using the HUD. Table 2 shows the range of errors present in various aircraft transparencies measured along a normal and then used at the installed angle. The error may also be calculated from the equation:

$$D = I + R - A$$

Where

D = True deviation
I = Angle of incidence at first surface
R = Angle of refraction at final surface
A = Wedge angle (apical angle of prism or wedge)

TABLE 2

Sighting Errors Due to Rotation of the Transparency From Measurements Along the Normal

Assume an average index of refraction of 1.5. Measure the angle of incidence of the pilot's line of sight (the angle between the line of sight and a perpendicular to the surface), and multiply the amount of angular deviation found by measuring along the "normal" by the multiplication factor given below.

Angle Incidence in degrees	Multiplication Factor	Angle of Incidence in degrees	Multiplication Factor
0	1.00	50	2.01
5	1.01	55	2.38
10	1.03	60	2.89
15	1.06	65	3.64
20	1.11	70	4.80
25	1.18	75	6.76
30	1.27	80	10.63
35	1.39	85	20.86
40	1.54	90	65.03
45	1.74		

Example:
Using the "normal" angular deviation method, an F-111 windscreen is determined to have 2 minutes (0.58 milliradians) angular deviation along BL 0.0 near the forward arch. The angle of incidence of the pilot's line of sight is determined to be 70 degrees in this area. The resultant actual angular deviation will then be 2 X 4.8 = 9.6 minutes (2.79 milliradians).

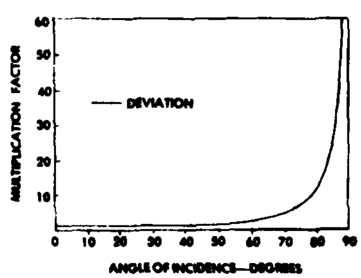

FIGURE 6. EFFECT OF ROTATION OF THE TRANSPARENCY ON DEVIATION AS MEASURED ALONG A NORMAL

SUMMARY OF TECHNIQUES

Following are summaries of methods of measuring angular deviation for most US aircraft equipped with HUDs. The maximum limits, method of obtaining data and method of analyzing data are from the source quoted on the first line of each summary. Comments about accuracy or applicability to operational conditions are the author's.

Aircraft:	A-10 Fairchild Document 160S310001E, 1 May 1979
Panel	Maximum Permissible Amount
Center Pane:	2 minutes of arc (0.58 MR)
Canopy:	3 to 5 minutes of arc (0.87 to 1.45 MR), depending on zone measured.
Side Panels:	8 minutes of arc. (2.32 MR)

Method of Measurement
The specimen (canopy) is held so that the line of sight between a telescopic sight equipped with a crosshair and a backlighted target passes through the part at right angles to the surface of the target (normal incidence). The target consists of graduated marks at 1-minute increments. The distance between scope and target is based on the absolute distance between graduations on the target, to maintain 1-minute intervals. The distance between scope and specimen is approximately 12 inches. (See Figure 7).

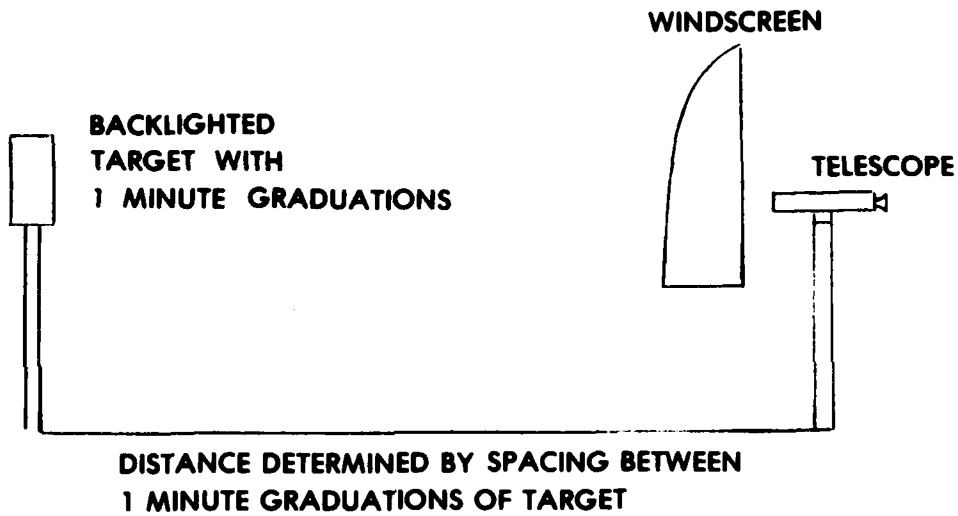

FIGURE 7. METHOD OF MEASURING THE A-10 WINDSHIELD

Sightings are taken both without and with the specimen in place. Angular deviation is recorded as the difference in position of the crosshair between the without and with specimen sightings.

Comments
Measurement taken at normal incidence. Subject to error when part rotated to installed position. See Table 2 and Figure 6 for estimated amounts of error.

Aircraft: F-5A, F-5E; Northrup Process Specification EO E37210, 22 Feb 1979

Panel	Maximum Permissible Amount	
Canopy:	0.5 grid	(14.8 minutes or 4.30 MR)
Windshield:	0.3 to 0.4 grid	(8.9 minutes or 2.58 MR to 11.8 minutes or 3.44 MR)

Method of Measurement
Double exposure photographic technique. Camera is placed at pilot's design eye position; gridboard consisting of 1/16 inch lines on 1 inch centers is placed 151.1 inches (3.84 meters) from design eye (equivalent to 114.7 inches from supercritical area). An exposure is first made without the specimen in place. The canopy is then inserted in the optical path between camera and gridboard, with STA 240.9 at design eye (this approximates the installed angle position). It is then rotated upwards from its flat resting position by 45 degrees before with-canopy photos are taken (see Figure 8A).

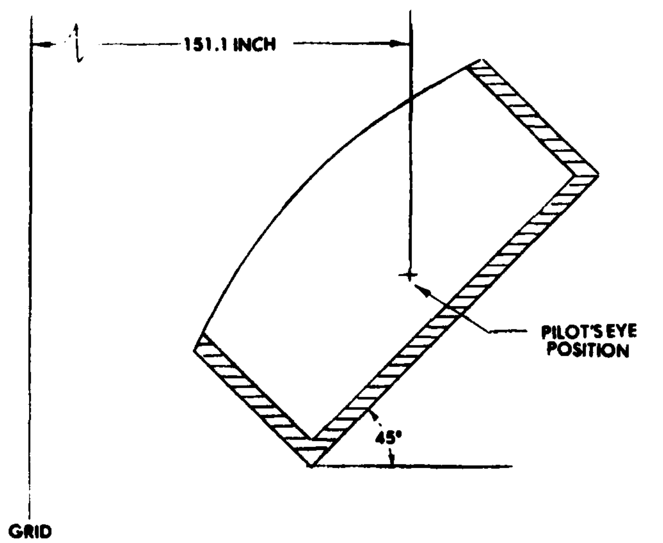

FIGURE 8A. METHOD OF MEASURING THE F-5 CANOPY

The windshield is measured in a similar manner, except it is kept in the approximate installed angle, an appropriate distance in front of design eye to simulate installation on the aircraft (see Figure 8B).

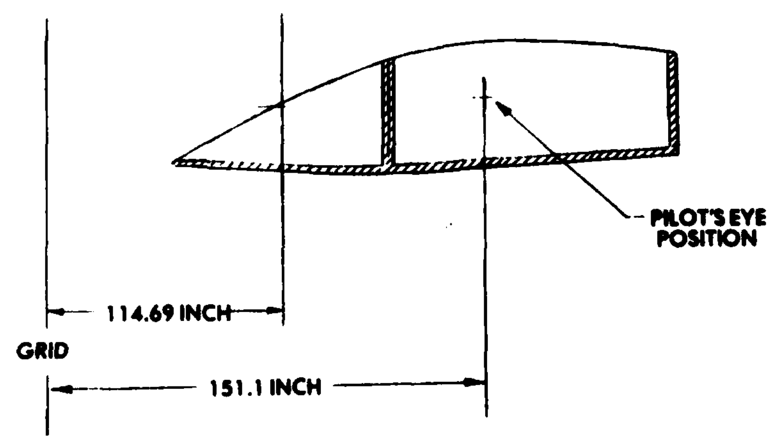

FIGURE 8B. METHOD OF MEASURING THE F-5 WINDSHIELD

Comments
Does not determine absolute angular deviation. Second photographic image position shifted by the sum of angular deviation components and lateral displacement components. Rotation of canopy further confuses results.

Aircraft: F16 General Dynamics Specification 16ZK002D, as amended

Maximum Permissible Amount

Canopy: No more than 3 MR maximum or 1 MR RMS deviation from a "best fit" cosine curve produced from a series of 40 datapoints taken through the HUD equivalent zone of the canopy.

Methods of Measurement

Method 1:
A theodolite is placed at design eye position and sighted on a target 100 feet away. The target consists of a grid of lines drawn at 1 MR increments. The canopy is interposed in the line of sight in the installed angle. A series of readings is taken at predetermined azimuth and elevation angles. The canopy is then elevated or depressed so that the readings are repeated, using lines of sight anywhere from 2 inches below design eye to 2 inches above design eye. Angular deviation is recorded as the amount of apparent displacement of the theodolite crosshairs on the target.

Comments
Does not determine absolute angular deviation. Image positions as seen through the transparency are shifted by the sum of angular deviation components and lateral displacement components.

Method 2:
A laser is placed at design eye position and aimed at a target 100 feet away. The target consists of a precision mylar grid pattern. The position of the laser spot is noted on the grid pattern. The canopy is interposed in the line of sight in the installed angle. A series of readings is taken at predetermined azimuth and elevation angles. The canopy is then elevated or depressed so that the readings are repeated, using lines of sight anywhere from 2 inches below design eye to 2 inches above design eye. Angular deviation is recorded as the amount of displacement of the laser spot on the target (in inches) divided by 1200.

Comments
Does not determine absolute angular deviation. Image positions as seen through the transparency are shifted by the sum of angular deviation components and lateral displacement components.

Method 3:
A collimated light source (target effectively at infinity) is placed at design eye and aimed at a receiver 4-6 feet away. The receiver consists of a field lens, a beamsplitter and two CCD arrays located at the focal plane of the lens. The positions of the light image on the CCD arrays are recorded and displayed in milliradians electronically. The canopy is interposed in the line of sight in the installed angle. A series of readings is taken at predetermined azimuth and elevation angles. The canopy is then elevated or depressed so that the readings are repeated, using lines of sight anywhere from 2 inches below design eye to 2 inches above design eye. Angular deviation is recorded as the difference between no canopy and with canopy readings.

Comments
"Pure" angular deviation may be measured by this method.

Method 4:
A collimated light source (target effectively at inifinity) is placed at design eye and aimed at a theodolite 11 feet away. The theodolite is focused on the collimated image of a crosshair. The canopy is interposed in the line of sight in the installed angle. A series of readings is taken at predetermined azimuth and elevation angles, realigning the theodolite at each reading. The light source is then elevated or depressed so that the readings are repeated, using lines of sight anywhere from 2 inches below design eye to 2 inches above design eye. Angular deviation is recorded as the difference between no canopy and with canopy theodolite alignment, coverted to milliradians.

Comments
"Pure" angular deviation may be measured by this method, if light source and theodolite are properly aligned and calibrated.

Analysis (for all four methods)
Data are then entered into a computer and reduced to a series of coefficients describing a cosine curve (for elevation errors) or a straight line (for azimuth errors). The coefficients are converted to values which are later input to the HUD computer to "correct" the aiming error resulting from angular deviation variations.

Aircraft:	F-15 McDonnell Douglas Process Specification 21232
Panel	Maximum Permissible Amount
Windshield:	1.8 minutes of arc (0.523 MR) in critical optical area
	3.5 minutes of arc (1.018 MR) in Zone 1 optical areas

Method of Measurement
The optical deviation is determined by using a low-power telescope located near the projector or an observer located near the screen to observe the image of a line projected through the windshield. For measurement of azimuth deviation, the line is produced by a 35 mm projector located 10 ft 7 inches from the center of rotation of the windshield (windshield cone axis) as the latter is mounted on a turntable so the line of sight passes at a normal through the transparency. The image of the line falls on a screen located 26 ft 5 inches from the center of rotation of the windshield. If this image falls within two solid parallel lines (the lines being 0.157 or 0.305 inches from a broken parallel line bisecting the distance between the solid parallel lines, the part "passes." See Figure 9A for a diagram similar to this arrangement.

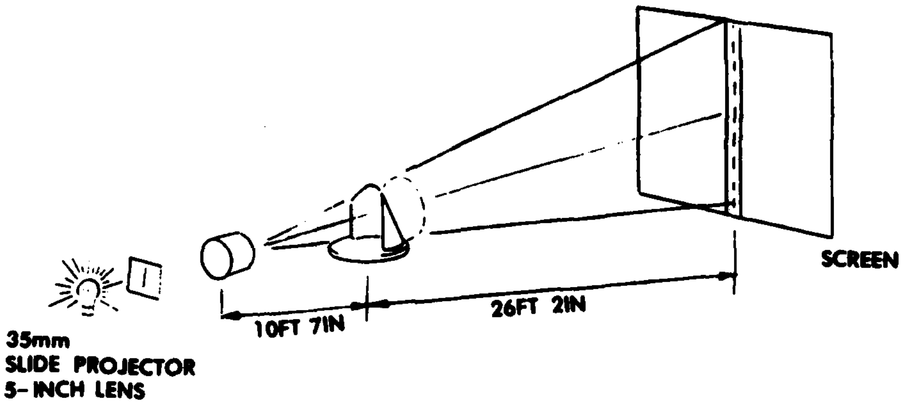

FIGURE 9A. METHOD OF MEASURING THE F-15 AND F-18 WINDSHIELD (AZIMUTH)

For elevation deviation, the projection screen is arranged as described above, but the translation axis of the windshield as well as the windshield surface are set normal to the projection axis. The projector is between 3 feet and 10 feet 7 inches from the surface of the transparency. Again, a line is projected through the windshield to fall on the screen. If the projected line falls outside of the solid parallel lines, the part "fails." Figure 9B diagrams a similar arrangement.

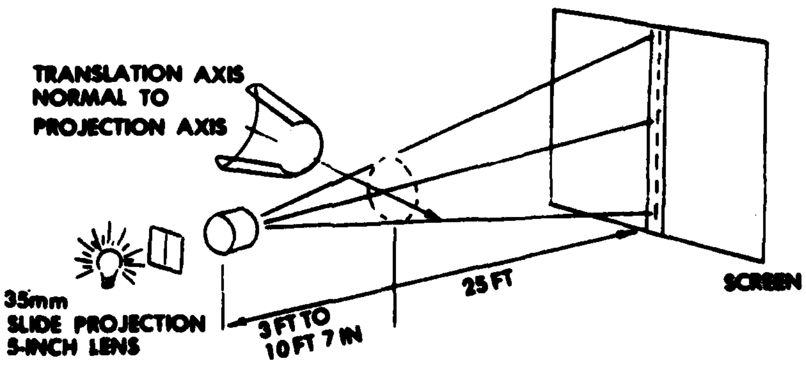

FIGURE 9B. METHOD OF MEASURING THE F-15 AND F-18 WINDSHIELD (ELEVATION)

Comments
Measurement taken at normal incidence. Subject to error when part rotated to installed position. The effective measurement area at any one time of the windshield under test is related to the projector lens focal length, aperture and distances involved. The height of this area is controlled to be 36 inches.

Aircraft:	F-18 McDonnell Douglas Process Specification 21229
Panel	Maximum Permissible Amount
Windshield:	0.4 minutes of arc (0.116 MR) in critical optical area
	1.0 minutes of arc (0.29 MR) in center optical area
	2.0 minutes of arc (0.58 MR) in outer optical area

Method of Measurement
The optical deviation is determined by using a low-power telescope to observe the image of a line projected through the windshield. For measurement of azimuth deviation, the line is produced by a projector located 10 ft 7 inches from the center of rotation of the windshield (windshield cone axis) as the latter is mounted on a turntable so the line of sight passes at a normal through the transparency. The image of the line falls on a screen located 26 ft 2 inches from the center of rotation of the windshield. If this image falls within two parallel lines (the lines being 0.070, 0.174, 0.349 or 0.698 inches apart, depending on the optical area being measured), the part "passes." See Figure 9A for a diagram of this arrangement.

For elevation deviation, the projection screen is arranged as described above, but the translation axis of the windshield as well as the windshield surface are set normal to the projection axis. Again, a line is projected through the windshield to fall on the screen. If the projected line falls outside of the parallel lines, the part "fails." Figure 9B diagrams this arrangement.

The separations of the lines as indicated earlier were selected because of the following relationships:

Separation inch	=	Minutes of Arc
0.035		0.40
0.087		1.0
0.174		2.0
0.349		4.0

The two parallel lines enclose a space bisected by a third parallel line. Each of the outer parallel lines is separated from the inner line by the amount in the above table.

Comments
Measurement taken at normal incidence. Subject to error when part rotated to installed position. The effective measurement area at any one time of the windshield under test is related to the projector lens focal length, aperture and distances involved.

Aircraft:	**F-111 (General Dynamics) ATP 601-E**
Panel	**Maximum Permissible Amount**
Windscreen:	**4 minutes of arc**

Methods of Measurement
1. "Double Vision Method".
Observation of secondary image of a point source as seen through the windshield. Inspector's eye is located 12 inches from windscreen. Line of sight passes at a normal through the windscreen to a graticule target 25 feet from the transparency (Figure 10A).

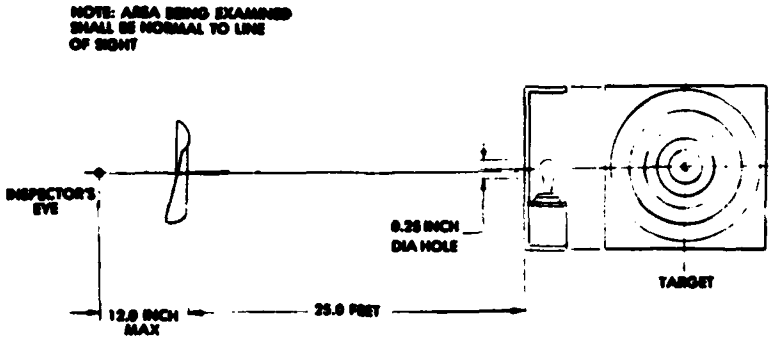

FIGURE 10A. DOUBLE VISION METHOD FOR F-111 WINDSCREENS

2. "Laser Method".
The part is held so a laser beam located 18 inches from the windscreen passes along a normal to the surfaces of the transparency. The displacement of this beam as measured at a (United Detector Technology PN SC/10) detector located at the target plane 18 inches away is converted to minutes of angular deviation (Figure 10B).

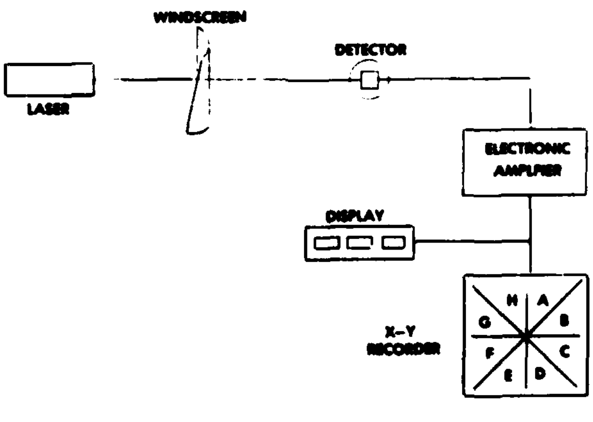

FIGURE 10B. LASER METHOD FOR F-111 WINDSCREENS

Analysis
A "deviation map" of the entire windscreen is made by measuring the deviation values at the centers of a 3 x 3 inch square grid superimposed on the windscreen. Coded deviation vectors include both direction (A... B... C...) and magnitude (in minutes). A complicated graphic procedure, using templates and overlays is then used to determine the angular deviation within the windshield's critical area. If the deviation direction or magnitude exceeds the allowable shape or size of a specified template, the windshield fails the criterion. The magnitude of the "failure" vector may be between 4 and 9 minutes, depending on the zone measured.

Comments
Measurement taken at normal incidence. Subject to error when part rotated to installed position.

CONCLUSION AND RECOMMENDATIONS

Of the several aircraft studied, there are many different methods of measuring angular deviation, most of which do not give equivalent data, or do not indicate the angular deviation and resultant aiming error experienced by the pilot. Two currently used methods of measuring angular deviation give both equivalent data and data that are not contaminated by lateral displacement errors. Both of these latter methods use a collimated light source and an optical receiver (either a theodolite or an optoelectronic device) with an imaging system, with the transparency held in the installed position. If the accurate measurement of angular deviation is a necessary part of quality control procedures to be used with HUD equipped aircraft, the methods used should measure angular deviation rather than an artifact. If standardization of methodology, easy comparison of data and cross-correlation of effects is desired, methods which give equivalent results should be employed. The only methods currently in use which meet these criteria use collimated light from the target to image in a receiver containing a field lens, with the transparency held in an angular position as if it were installed on the airframe. We highly recommend the adoption of methods of measuring angular deviation that meet these criteria of accuracy, validity and comparability.

APPENDIX A

TABLES OF LATERAL DISPLACEMENT FOR VARIOUS THICKNESSES OF MATERIAL

Assuming an average index of refraction of 1.5 and a parallel-sided optical flat 0.5 in thick located 1200 inches from a measuring instrument, the sighting error induced by the method of measurement is shown below.

Angle of Incidence Degrees	*Displacement Inch*	*Sighting Error Milliradian*
65	0.276	0.230
66	0.286	0.238
67	0.295	0.246
68	0.305	0.254
69	0.314	0.262
70	0.324	0.270
71	0.333	0.277
72	0.342	0.285
73	0.352	0.293
74	0.361	0.301
75	0.370	0.308
76	0.379	0.316
77	0.389	0.324
78	0.398	0.331
79	0.407	0.339
80	0.416	0.346
81	0.425	0.354
82	0.433	0.361
83	0.442	0.368
84	0.451	0.376
85	0.459	0.383

Assuming an average index of refraction of 1.49 and a parallel-sided optical flat 0.71 in thick located 151 inches from a measuring instrument, the sighting error induced by the method of measurement is shown below.

Angle of Incidence Degrees	*Displacement Inch*	*Sighting Error Milliradian*
65	0.414	0.345
66	0.424	0.354
67	0.436	0.363
68	0.447	0.372
69	0.458	0.382
70	0.470	0.392
71	0.482	0.401
72	0.493	0.411
73	0.505	0.421
74	0.517	0.431
75	0.529	0.441
76	0.542	0.451
77	0.554	0.461
78	0.566	0.472
79	0.578	0.482
80	0.591	0.492
81	0.603	0.502
82	0.615	0.513
83	0.627	0.523
84	0.640	0.533
85	0.652	0.543

(Data similar to F-5)

Assuming an average index of refraction of 1.5 and a parallel-sided optical flat 0.75 in thick located 1200 inches from a measuring instrument, the sighting error induced by the method of measurement is shown below.

Angle of Incidence Degrees	*Displacement Inch*	*Sighting Error Milliradian*
65	0.415	0.345
66	0.429	0.357
67	0.443	0.369
68	0.457	0.381
69	0.471	0.393
70	0.485	0.404
71	0.499	0.416
72	0.513	0.428
73	0.527	0.440
74	0.541	0.451
75	0.555	0.463
76	0.569	0.474
77	0.583	0.486
78	0.596	0.497
79	0.610	0.508
80	0.623	0.520
81	0.637	0.531
82	0.650	0.542
83	0.663	0.553
84	0.676	0.563
85	0.689	0.574

(Data similar to thick F-16)

Assuming an average index of refraction of 1.5 and a parallel-sided optical flat 0.63 in thick located 1200 inches from a measuring instrument, the sighting error induced by the method of measurement is shown below.

Angle of Incidence Degrees	*Displacement Inch*	*Sighting Error Milliradian*
65	0.369	0.308
66	0.379	0.316
67	0.389	0.324
68	0.399	0.332
69	0.409	0.341
70	0.419	0.349
71	0.429	0.358
72	0.440	0.366
73	0.450	0.375
74	0.461	0.384
75	0.471	0.393
76	0.482	0.402
77	0.493	0.411
78	0.504	0.420
79	0.514	0.429
80	0.525	0.438
81	0.536	0.447
82	0.547	0.456
83	0.558	0.465
84	0.568	0.474
85	0.579	0.482

(Data similar to thin F-16)

APPENDIX B

METHODS USED TO MEASURE ANGULAR DEVIATION

Aircraft	Measurement Angle	Device	Target
A-10	Normal incidence	Telescope	Uncollimated
F-5	Installed angle	Photos	Uncollimated 50 in
F-15	Normal Incidence	Projector	Uncollimated
F-16	Installed angle	Telescope	Uncollimated 100 ft
	Installed angle	Laser	Uncollimated 100 ft
	Installed angle	Optoelectronic	Collimated
	Installed angle	Theodolite	Collimated
F-18	Normal incidence	Projector	Uncollimated
F-111	Normal incidence	Reflection	Uncollimated
	Normal incidence	Laser	Collimated

APPENDIX C

COMPUTATION OF ACTUAL ANGULAR DEVIATION EXPERIENCED AS A RESULT OF TILTING TRANSPARENCY

Angle of Incidence In Degrees	*Multiplication Factor*	*Angle of Incidence In Degrees*	*Multiplication Factor*
0.00	1.00		
1.00	1.00	46.00	1.79
2.00	1.00	47.00	1.84
3.00	1.01	48.00	1.90
4.00	1.01	49.00	1.95
5.00	1.01	50.00	2.01
6.00	1.01	51.00	2.08
7.00	1.02	52.00	2.15
8.00	1.02	53.00	2.22
9.00	1.02	54.00	2.30
10.00	1.03	55.00	2.38
11.00	1.03	56.00	2.47
12.00	1.04	57.00	2.56
13.00	1.05	58.00	2.66
14.00	1.05	59.00	2.77
15.00	1.06	60.00	2.89
16.00	1.07	61.00	3.02
17.00	1.08	62.00	3.16
18.00	1.09	63.00	3.30
19.00	1.10	64.00	3.46
20.00	1.11	65.00	3.64
21.00	1.12	66.00	3.83
22.00	1.14	67.00	4.04
23.00	1.15	68.00	4.27
24.00	1.16	69.00	4.52
25.00	1.18	70.00	4.80
26.00	1.19	71.00	5.10
27.00	1.21	72.00	5.45
28.00	1.23	73.00	5.83
29.00	1.25	74.00	6.27
30.00	1.27	75.00	6.76
31.00	1.29	76.00	7.32
32.00	1.31	77.00	7.96
33.00	1.34	78.00	8.71
34.00	1.36	79.00	9.59
35.00	1.39	80.00	10.63
36.00	1.41	81.00	11.88
37.00	1.44	82.00	13.41
38.00	1.47	83.00	15.31
39.00	1.51	84.00	17.72
40.00	1.54	85.00	20.86
41.00	1.58	86.00	25.03
42.00	1.61	87.00	30.73
43.00	1.65	88.00	38.68
44.00	1.70	89.00	49.82
45.00	1.74	90.00	65.03

To use this table for any aircraft transparency whose angular deviation is measured along a normal, first determine the angle of incidence of the line of sight at the point of interest on the transparency (transparency held at installed angle), then multiply the 'NORMAL' angular deviation by the factor above.

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